Forest Research
Extension Note
Vancouver Forest Region
2100 Lableux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

EN-014 Hydrology March 2002

KEYWORDS:
Streamflow, dilution gauging, current metering, Russell Creek

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BRITISH COLUMBIA

Alternative methods of flow rating in small Coastal streams

by Robert Hudson and John Fraser[1]

ABSTRACT

Dilution is one of three standard methods for measuring streamflow in natural channels. The basic concept is to add a measured quantity of a tracer to the flow and then observe its concentration at a point downstream. The greater the flow, the more dilute the tracer will be for a given quantity added. Although not routinely used at present, dilution may have the potential to be a reliable alternative method of measuring streamflow in turbulent channels.

Trials were conducted using salt dilution at several creeks in the Tsitika River watershed of Vancouver Island and the Roberts Creek area on the Sunshine Coast of BC. The methodologies of application and measurement were studied, and the results compared with results achieved using the other two standard methods, current metering and weir rating. For accuracy, the dilution method compared favorably with current metering for measuring small turbulent streams, and offered several practical and cost advantages. Overall, the results validate salt dilution as a viable alternative to use where current metering is not suitable.

1.0 INTRODUCTION

There are essentially three standard methods of measuring streamflow in natural channels: cross-sectional current metering, dilution methods, and the use of weirs or flumes. Each method is suited to a different type of channel.

Current metering is well suited to large, low-gradient rivers where flow conditions are close to laminar, whereas dilution methods are better suited to smaller, steeper-gradient channels with more turbulent flow. These two methods are used in conjunction with channel control to develop a rating curve to convert stage measurements to stream discharge. In small channels, weirs can be used to convert stage directly into discharge, using a mathematical formula based on the weir properties, without the need to measure flow directly. Weirs are commonly used where highly precise measurements of relatively low flow volumes are needed, such as the measurement of streamflow in research watersheds or irrigation ditches.

Dilution methods are not routinely used, despite having been well described by several authors (Kite, 1993, Day, 1977a, Church & Kellerhauls, 1970, Elder & Kattleman, 1990). Water Survey of Canada (WSC) relies almost exclusively on current metering to gauge stream flow in larger creeks and rivers, even in situations where an alternative method such as dilution may be more appropriate. Regardless, rating curves are derived based on the assumption that the error in measuring flow is within 5%, even though the basic assumptions of the method may be violated by turbulent conditions, irregular bed geometry, and other factors.

In response to a need for a reliable method of rating streamflow in turbulent channels, the salt dilution method has been developed and imple-

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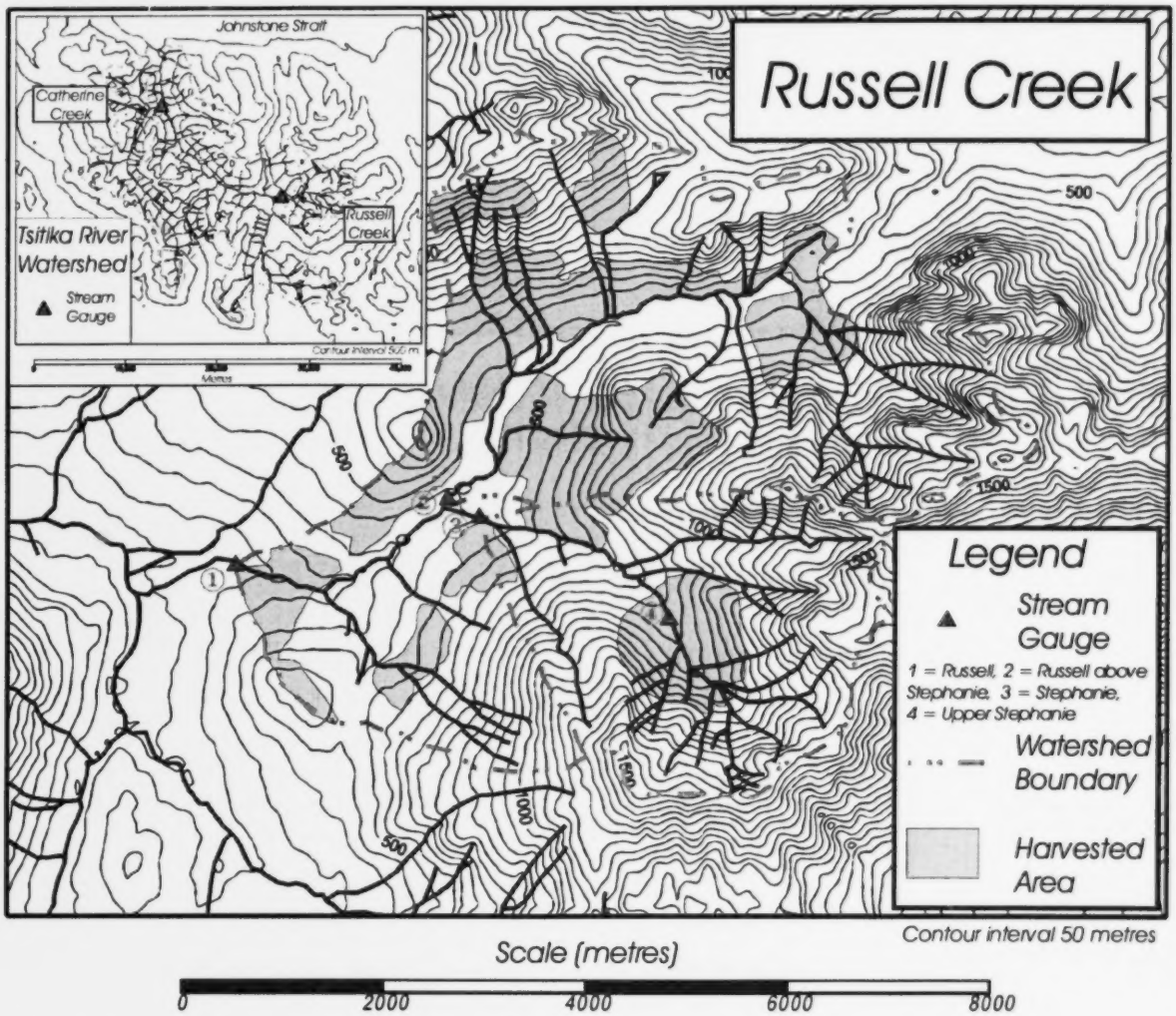


Figure 1. Map of Russell Creek showing the stream gauge sites.

mented at Russell Creek, and has now become the primary method of measuring streamflow at that site (Figure 1). Russell Creek is a tributary of the Tsitika River on northeastern Vancouver Island, and is the site of ongoing sediment budget research. Russell Creek watershed has been described in detail by Hudson (2001a, b, c). Trials have been conducted in mainstem channels and in gullies with equal success.

This report focuses on the application of salt dilution gauging to creeks with drainage areas ranging from 0.2 to 46 km^2, at Tsitika River (including Russell and Catherine Creeks) and at Roberts Creek, located on the Sunshine Coast near Sechelt. The purpose of this paper is to describe the salt dilution method and discuss some practical aspects of its application, and to present an alternative approach to developing rating curves in alluvial channels.

2.0 THE SALT DILUTION METHOD

The basic idea of any dilution method is to add a measured quantity of a tracer to the flow and then observe its concentration at a point downstream of the injection point where it is completely mixed with the flow. The greater the flow, the more dilute the tracer will be for a given quantity added.

There are two commonly used tracers: rhodamine dye and common table salt. The tracer can be added to the channel by continuous or slug injection. Slug injection is more commonly used, as it requires no additional equipment to add the tracer to the channel. In any case, the concentration of the tracer can be measured in the stream indirectly but with high precision. In the case of salt, there is a linear relationship between salt concentration and electrical conductivity. The equipment needed to measure electrical conductivity in streams is relatively inexpensive

and lends itself to automatic measurement with a data logger. Thus, there is potential to develop the salt dilution method into a fully automated streamflow rating method that can be applied remotely at times when it may be difficult for a human operator to gain access to the site.

The salt dilution method by slug injection was chosen as the most practical method to develop for general application. A Unidata 4-electrode temperature-compensated electrical conductivity probe with a dedicated micro logger was used to collect the instream conductivity data. The instrument is auto-ranging between 0 and 200,000 µS/cm, with an accuracy of ±0.5%. Using the slug injection approach, the salt can be added to the channel either as a saturated solution, or in dry undissolved form. Many trials were conducted using both variations of the method; examples of each variation are provided in the following discussion.

If a saturated solution is to be used, the conductivity of the solution is determined in advance by calibrating it in the approximate range expected within the channel after injection of the solution. A saturated solution can be made by dissolving about 2 kg of salt in 20 litres of stream water, depending on the temperature and background conductivity of the stream. A standard calibration procedure was used to calculate stock conductivity, as follows:

- Start with 1.98 litres of stream water;
- Add 20 ml of solution to the sample in 10 ml increments while measuring the conductivity of the resultant solution;
- The stock conductivity at each step is equal to the solution conductivity multiplied by the dilution factor. Using this procedure, the dilution factors at each step are 199 and 100 respectively;
- The two values are then averaged.

A typical measurement produces a wave of electrical conductivity in the stream shortly after the solution slug is added, according to the dispersion of the salt solution within the water column (Figure 2). The shape of the graph is similar to that of a streamflow hydrograph. The stream flow is then calculated by the following formula:

$$Q = \frac{V \cdot m_0}{A} \qquad (1)$$

where V is the volume of solution added to the stream and m_0 is the conductivity of the stock solution. A is the area under the dispersion curve. This is the shaded area in Figure 2, and can be calculated as:

$$A = \sum (m_t - m_1) T \qquad (2)$$

where m_t is the electrical conductivity at time t, m_1 is the background electrical conductivity in the channel and T is the time interval, usually five seconds. The method is best applied using a conductivity probe read by a data logger, allowing one operator to collect the measurement.

The example given in Figure 2 is for a flow measurement collected at upper Stephanie Creek, draining an area of 3.45 km^2. In this case, the conductivity of the stock solution was measured at 169327 µS/cm. Twenty litres of solution were used for the measurement, for a measured flow of 0.837 m^3/s.

As an alternative to injecting dissolved salt into the stream, Elder and Kattleman (1990) proposed a mass balance method based on slug injection of undissolved salt. The method is essentially the same as described above; instead of preparing and calibrating a salt solution for each measurement, a known mass

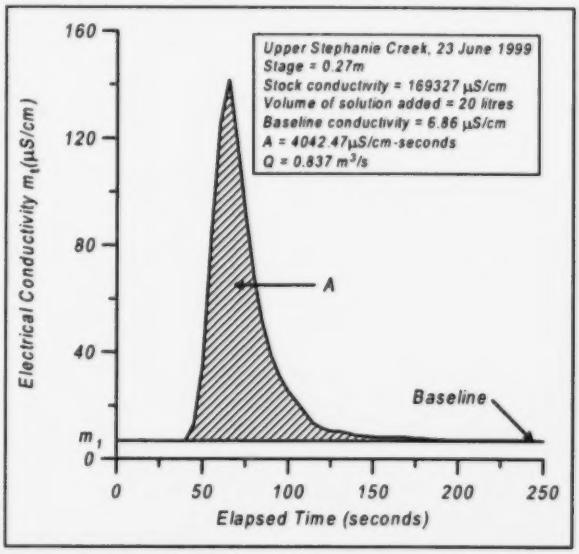


Figure 2. An example of a salt dilution measurement done at upper Stephanie Creek.

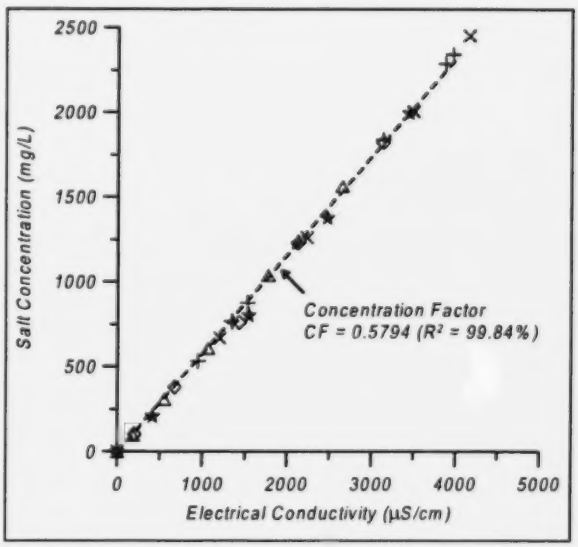


Figure 3. Results of several calibration trials of the electrical conductivity probe. Each symbol represents a different trial using either different batches of salt or different water. The regression line is for all data lumped together.

of salt is added to the stream and the flow is calculated as follows:

$$Q = \frac{M}{A \cdot CF} \qquad (3)$$

where M is the mass of salt added to the stream, and CF is the concentration factor, or the slope of the relationship between salt concentration and electrical conductivity.

Several calibrations were completed using different batches of table salt and water from various sources with background conductivities ranging from 10 to 80 µS/cm. The concentration factors were all very close, with no systematic differences within or between batches (Figure 3). Concentration factors for six separate calibration trials varied from 0.5645 to 0.5872. Thus, it was concluded that the differences in the calibration factors were due to random error. A standard CF derived from lumping all the calibration data together was calculated at 0.5794. The calibration factor is most likely a function of the instrument, as opposed to the salt or the water. There may be a slight non-linearity of the probe above a conductivity of 4000 µS/cm; however, peak in-stream conductivity levels that occurred as a result of these trials rarely exceeded 500 µS/cm (on one occasion, the conductivity peaked at 1449 µS/cm at Stephanie Creek).

3.0 ASSUMPTIONS AND SOURCES OF ERROR

The main assumptions of the method are as follows:

1. The salt must be completely mixed with the flow at the in-stream measurement point.

2. For slug injection, the salt must be added to the channel instantaneously.

3. There must be no local inflows between the injection and measurement points.

4. The measurement reach should be straight with no pools where the salt can become retarded and separated from the main flow.

Experience has shown that the first two assumptions are inviolable – if these assumptions are not met, the measurement will not work. The other assumptions are of minor importance in comparison. Table 1 summarizes the advantages and disadvantages associated with using either saturated solution or dry salt to apply the salt dilution method.

To meet assumption Number 1, the first criterion is that the measurement reach should be turbulent. The mixing reach at Russell Creek, located near the mouth, has several points where turbulence creates conditions suitable for mixing (Figure 4), whereas Stephanie Creek (Figure 5) is ideal for salt dilution, and cannot be rated by any other method.

A mixing length must be chosen to ensure complete mixing. There are various empirical equations to predict a mixing length (e.g., Day, 1977; Hershey, 1985). For example, Kite (1993) gives a formula to estimate the required mixing length as follows:

$$L = 250\sqrt{W \cdot D} \qquad (4)$$

where L is the mixing length, W is the average section width and D is the average section depth, all in metres. However, in reality, the required mixing length depends on the hydraulics of the measurement reach (Elder & Kattelmann, 1990). If a saturated solution is used, incomplete mixing or non-instantaneous injection are sources of random error, resulting in an in-stream conductivity hydrograph that is not smooth, indicating that the measurement has not been successful. If the mixing length is too long, then the conductivity hydrograph will be "damped" – that is, the peak will be reduced and the time base extended, but in the absence of local inflows, the area under the graph should be the same as for an optimum mixing length. However, if there is substantial inflow in the measurement reach, it will be difficult to establish a stable rating curve because the flow measurements may not correspond to measured stage.

If dry salt is used, the mixing length must also be long enough to ensure that the salt is fully dissolved before passing the sampling point. Complete dissolution depends on the water temperature and the velocity of flow. If the salt is not fully dissolved, then the in-stream conductivity will be low, and the flow will be over-estimated. Therefore, in practice, empirical formulae such as equation 4 might be of little use to estimate a mixing length. In a study of mountain streams in New Zealand, Day (1977b) reported that mixing lengths were considerably shorter than those predicted using an equation, and reported complete mixing at a length of 25 times the average width.

We have found that the best way to ensure full mixing is to choose an injection point that is turbulent enough to ensure

Table 1. Pros and cons of using salt solution vs. dry salt.

Issue	Pro	Con
Calibration	**Dry**: *standard calibration can be used*	**Solution**: *EC of stock solutions vary widely, each solution must be calibrated separately.*
Mixing length	**Solution**: *can be calculated, mixing is easily achieved.*	**Dry**: *must be determined by trial and error, particularly at high flow.*
Time to take measurement	**Dry**: *salt is pre-weighed, reducing time to collect the measurement.*	**Solution**: *solution must be prepared and calibrated before the measurement can be done.*
Quantity of tracer required	**Dry**: *flows of up to 15 m3/s can be measured with 20 kg of salt, which can be handled by one operator.*	**Solution**: *Maximum volume of solution that can be handled is about 60 litres; upper limit of measurable flow is about 3.2 m^3/s*
Handling of salt	**Solution**: *Independent of weather conditions once the solution is calibrated and the injection volume measured. Can be dumped off a bridge.*	**Dry**: *salt must be kept dry to dump into stream, difficult during wet weather. Cannot be dumped off a bridge because the salt will be dispersed by wind.*

Figure 4. Salt dilution gauging reach at Russell Creek looking upstream from the bridge. Drainage area at this point is 30.1 km².

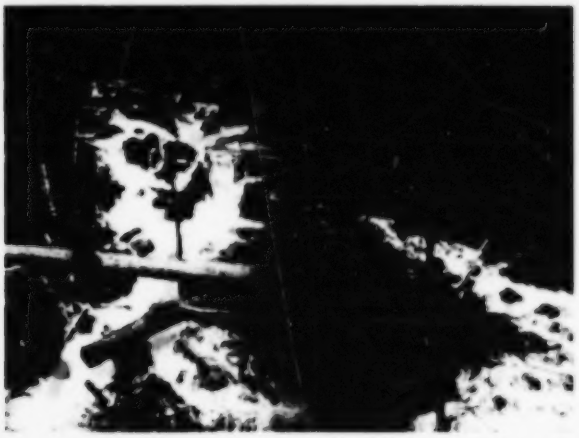


Figure 5. Stephanie Creek channel looking upstream from the bridge. Drainage area at this point is 8.6 km².

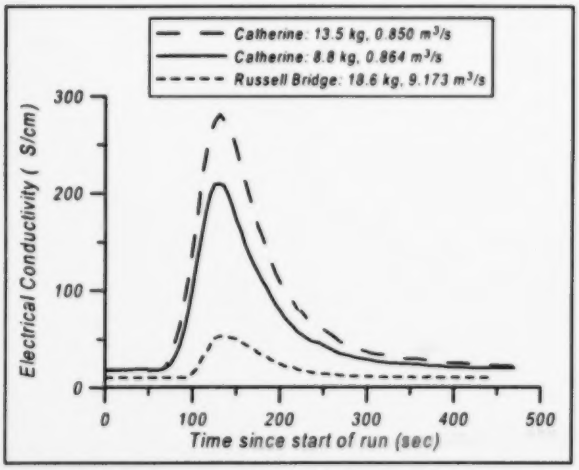


Figure 6. A comparison of three salt dilution trials at Catherine and Russell Creeks by dry salt injection to show the effect of varying mass on the measurement. At Catherine Creek, two measurements were done in succession using the same mixing length but different masses of salt. This shows that the mass of salt used is not critical; for a given flow, if the mass is increased, the area A increases proportionally. The measurement at Russell Creek represents a practical lower limit of 2 kg of salt per 10 m³/s of flow.

virtually instantaneous mixing (e.g., Figure 4). If a reach is chosen carefully, the mixing length can be reduced substantially. At the control section of Russell Creek, the channel width varies between about 5 and 7 metres. The average channel depth below the zero point on staff gauge is 0.36 metres. Equation 4 yields mixing lengths of 365 metres at a flow of 0.403 m³/s (stage below the staff gauge) and 638 metres at a flow of 9.09 m³/s (stage of 0.705 m). We started out with a much shorter mixing length and increased it experimentally until the measurements conformed to a stable rating curve. A mixing length of 120 metres was found to produce repeatable results at all flows that were measured, provided that the salt was injected at the point shown on Figure 4.

Assumption Number 4 is often violated in practice, since the method is generally applied to riffle-pool, cascade-pool or step-pool channels where it is difficult to avoid selecting a reach that contains pools. The presence of a pool in the measurement reach causes the tail of the conductivity hydrograph to be drawn out. Because of this, the tail of the distribution may be cut off due to the need to complete the measurement. Elder and Kattelmann (1990) and Day (1976) report that extended tails on the conductivity distribution create discrepancies in the result when the tail is a significant portion of the whole conductivity wave. However, we have found that it makes little difference to the result. For example, at Flume Creek, cutting off the tail of the distribution after 25 minutes of measurement caused overestimation of the flow by 1% on average, compared with a calculation based on allowing the conductivity to return to baseline levels.

Using dry salt injection, clumping of the salt can also cause the distribution tail to be extended. If this occurs, theoretically the method will still work, but it becomes difficult to determine the difference between the end of the conductivity wave and background conductivity. The solution to this problem is to ensure that the peak conductivity is high compared with the background conductivity, and that the salt is kept dry before adding it to the flow, to ensure rapid dissolution.

There are also formulae to estimate the required volume of solution. However, we have found that in practice, the quantity of salt injected is not critical, particularly with a multi-ranging instrument. The volume of solution or mass of dry salt must be known as precisely as possible, and it must be sufficient to register on the conductivity probe such that the peak conductivity is at least 50 mS/cm above background, assuming a stable background conductivity.

For example, at Catherine Creek (Figure 1), two trials were conducted in succession using the same mixing length and different masses of salt (Figure 6). In the first trial, 13.5 kg of salt were added to the stream, and in the second trial, 8.8 kg were added at flows of 0.850 and 0.864 m^3/s respectively. For a given flow and mixing length, the only difference between the two trials was the magnitude of the peak conductivity. In a different trial carried out at Russell Creek, 18.6 kg of salt was added at a flow of 9.173 m^3/s. The background conductivity was 10.3 mS/cm and the peak was 53.8 mS/cm. Thus, the ratio of the peak to background conductivity should be a minimum of 5. This establishes a practical limit to the method, according to how much salt an operator can dump into the creek at one time.

These were all successful measurements, suggesting a minimum quantity of salt required for the measurement. As a minimum, at least 20 kg of salt are needed to measure a flow of 10 m^3/s. This is equivalent to 100 litres of salt solution. Clearly, at 100 kg this is too heavy to be injected instantaneously into the channel by a single operator, but the 20 kg of dry salt is manageable. At higher flows (e.g. 40 m^3/s, which is in the order of the highest flows recorded at Russell Creek), about 500 litres of salt solution would be required, which renders salt dilution by saturated solution impractical.

In both cases, an accurate calibration is essential. An error in the calibration will result in an equivalent error in the measured flow. However, the potential for error in the calibration of solutions is fairly high, particularly since the calibration must be done in the field. For dry salt, calibration trials suggest that a standard calibration can be used, as long as the same instrument is used to measure electrical conductivity each time.

In summary, the following considerations are critical to the success of the measurement:

- The measurement reach must be turbulent;
- The salt must be injected instantaneously;
- The mixing length can be estimated at 20 to 25 times the mean channel width as a starting point, but a final length should be arrived at by trial;
- The minimum required mass of salt is 2 kg per 1 m^3/s of flow, assuming the background conductivity is stable;
- Notwithstanding the above, the peak conductivity should be a minimum of 5X the background if the background is stable, and if the tail of the distribution is short;
- These are minimum requirements and should only be applied at high flow in order to get maximum use out of the method;
- To deal with the potential for drawn-out conductivity distribution tails, try to maximize the ratio of peak to background conductivity to optimize measurement precision.

4.0 COMPARISON OF SALT DILUTION AND OTHER GAUGING METHODS

4.1 COMPARISON WITH CURRENT METERING

Salt dilution gauging has been compared favorably with current metering as a gauging method. In many cases, where conditions allowed, the two methods have been used side-by-side. For example, at upper Stephanie Creek (Figure 1), both turbulent and laminar flow reaches were found in close proximity to each other so that both methods could be performed for comparative purposes. Both saturated solution and dry salt injection were used for the salt dilution measurements. A rating curve based on salt dilution is defined by a simple exponential function (Figure 7), with an RMS error of 5%. The measurements collected by current metering fell close to the rating curve as defined above, but with an RMS error of 10.7%. Thus, the current metering measurements act as an accepted standard to validate the accuracy of the salt dilution measurements, while the error associated with each type of measurement suggests that salt dilution is the more precise method.

Salt dilution trials have been conducted at other sites as well, including Russell Creek above Stephanie confluence and Stephanie Creek (Figure 1). At Russell Creek above Stephanie, a rating curve was developed based on a combination of current meter and salt dilution measurements with results similar to those described above for upper Stephanie. At Stephanie Creek, there was no control reach suitable for current metering near the bridge, so a rating curve was constructed which relied on salt dilution

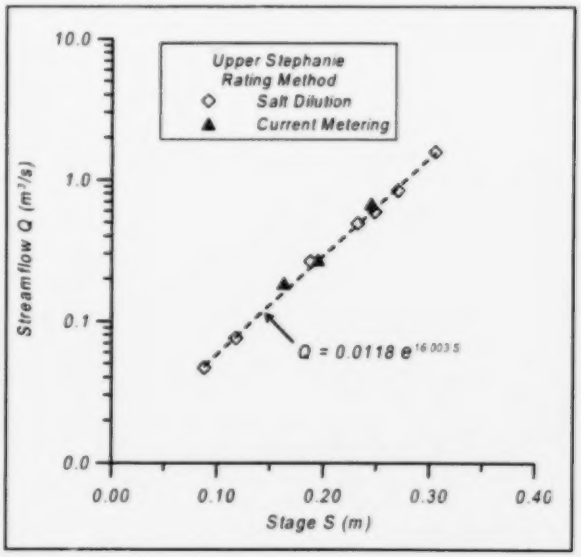


Figure 7. A rating curve developed for upper Stephanie Creek based on salt dilution measurements. The curve is a simple Type I exponential function. Measurements collected by current metering at the same site are comparable to the salt dilution measurements but have greater error with respect to the rating curve.

measurement alone. At that site, the flows that were calculated using that rating curve were found to agree closely with the difference between flows at Russell Main and at Russell Creek above Stephanie confluence.

4.2 COMPARISON WITH WEIR RATING

At Flume Creek on the Sunshine Coast, salt dilution was used to rate site F1 (Mainstem of Flume Creek at the Roberts-Flume Forest Service road, Figure 8). A 140° broad-crested concrete weir was constructed in the summer of 1994 to rate the flow, but the steep channel gradient and lack of a weir pond caused the weir to fill in with gravel over the first season of operation. As a result, the creek had to be rated by an alternate method. The rating curve was developed based on salt dilution by slug injection of saturated solution (Figure 9). The curve is described by a Type V exponential function. If the data point at a head of 48 cm and flow of 827 litres/sec is excluded, then the overall RMS error is 7.1%. Flume Creek at F1 has two tributaries, F4 and F5, each of which is gauged by a 90° sharp-crested weir. The drainage areas of F4 and F5 comprise 85% of the area of F1. Therefore, the following equation serves to validate the rating curve:

$$Q_{F1} \cong C(Q_{F4} + Q_{F5}) \qquad (5)$$

where the multiplier C is expected to be roughly equal to 1.18, which is the ratio of the area of F1 over the combined area of F4 and F5. Equation 5 should be true on the average; however, some deviation is expected due to the differences in watershed response. As an example, during a typical flow sequence from 15 - 31 December, 2000 (Figure 10), the value of C varied from

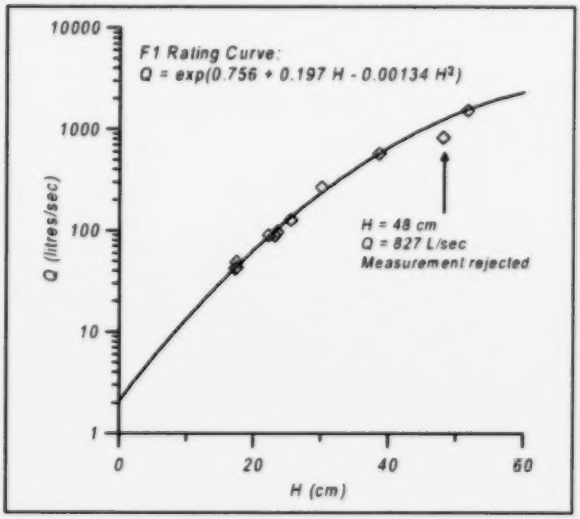


Figure 9. (Above) Rating Curve for F1, Flume Creek, derived from salt dilution gauging with saturated solution.

Figure 10. (At right) Example of a flow sequence at Flume Creek and showing agreement between weir rating (F4 + F5) and salt dilution (F1). On the average, the flow ratio is equal to the area ratio, allowing for differences in flow due to differences in precipitation distribution.

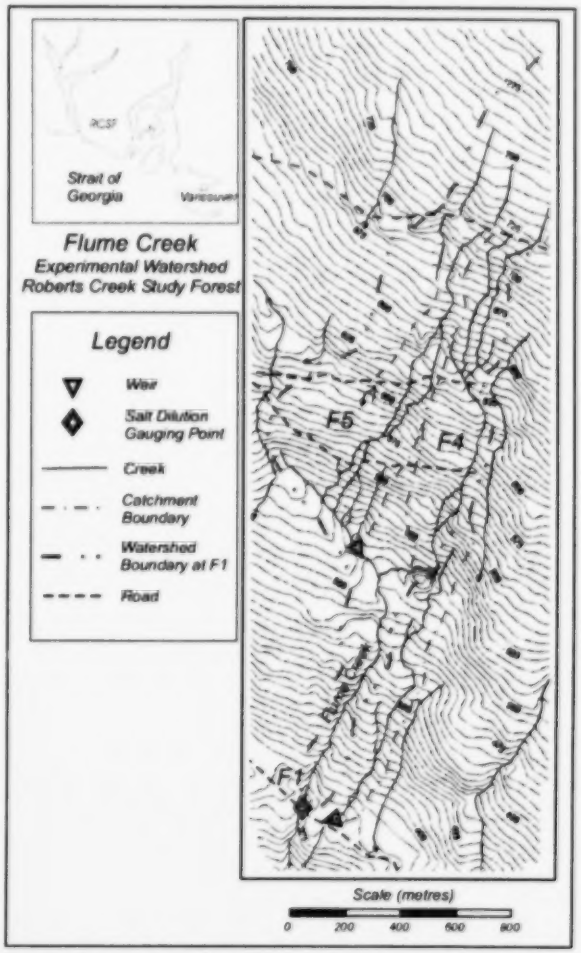
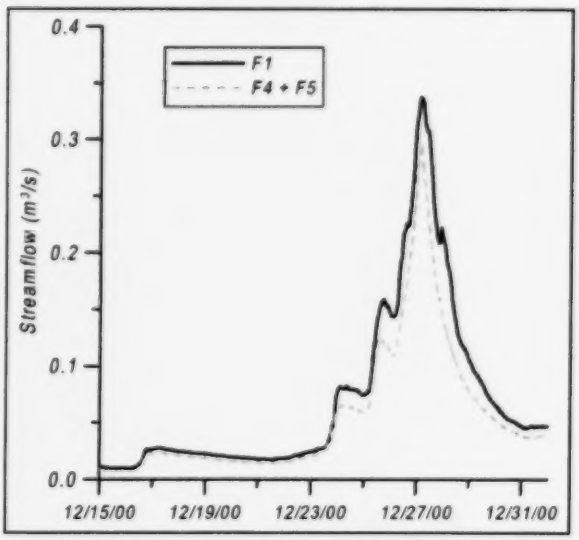


Figure 8. Flume Creek watershed (adapted from Hudson, 2001d).



about 1.0 on the rising limb on December 23 to a maximum of 1.5 on the falling limb just after the peak. The average value of C was 1.19 over the low flow period from December 15 to 22, and 1.22 over the whole sequence. Total flow volume was calculated for F1 for the period using the flows derived from the rating curve and from flows derived from equation 5, using a fixed value of 1.18 for C. The two flow volumes agreed to within 6.5%, and the discrepancy is due in part to precipitation distribution patterns in the watershed.

The above establishes the salt dilution method as an operationally viable method of gauging streamflow, comparing favorably in accuracy and precision with both current metering and weir rating.

5.0 CASE STUDY: RATING CURVE DEVELOPMENT AT RUSSELL CREEK

At Russell Creek, Water Survey of Canada collected 27 measurements of streamflow by current metering between November 1991 and the end of 1999. Based on these measurements, 12 different rating curves were developed to determine streamflow. There was a major shift in gauge height in the fall of 1995. This shift most likely occurred between the 8th and 17th of November in response to events with peak flows of 43.0 and 42.4 m^3/s respectively, the largest peak flows recorded at Russell Creek. The drop in gauge height for a given flow indicates lowering of the bed due to channel scour, which is consistent with extreme peak flows (Figure 11). After the shift in gauge height, WSC identified five different rating curves in order to meet the 5% error criterion. It is therefore necessary to assume that "large" peak flows are responsible for changes in the channel bed, which result in shifts in the rating curve (Table 2). Therefore, when it is apparent that a rating curve shift has occurred between measurements, the shift is applied at the time of the largest peak flow that occurred between those measurements.

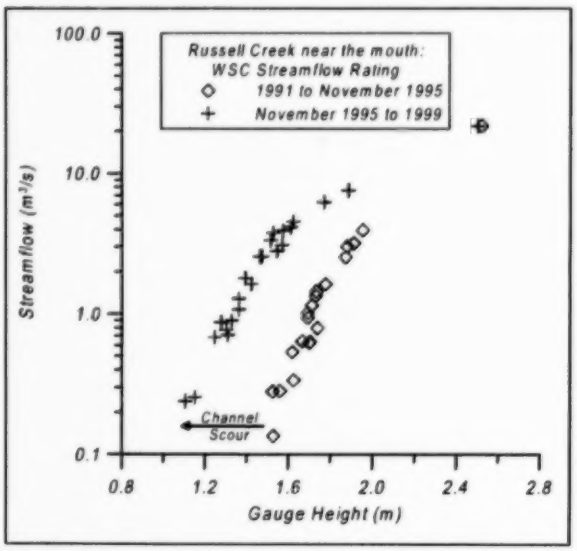


Figure 11. Stream gauging measurements collected by Water Survey of Canada (WSC) at Russell Main from November 1991 to June 1999. The drop in gauge height was caused by channel erosion during a sequence of high flow events in November 1995.

It seems that in order to maintain the assumption that the measurement error is within 5%, it is necessary to develop rating curves based on data that is so sparse that the curve violates statistical assumptions. Since the assumptions of the current metering method are also violated by in-stream conditions, a different approach to developing rating curves is warranted. If we assume that the measurement error is as high as 10%, then the number of rating curves in effect since November 1995 is reduced to two for low – medium flow with a common high flow curve. Those curves are defined by exponential functions (Figure 12). This represents a significant simplification in data analysis, and a more realistic treatment of the measurement data and associated errors.

Under the scenario described above, there is a break point in the data at a flow of about 4 m^3/s, representing a transition from low to high flow conditions. The low-end rating curves are defined by Type V exponential functions, and the common high-end curve by a Type I exponential function (Sit and Poulin-Costello, 1994). The overall RMS error for the data set is 5.5%. If we assume that the error on individual measurements can be as high as 15% using current metering, then the break point can be ignored and two rating curves can each be described by a single exponential curve. In this case, the Chapman-Richards curve was found to provide a good fit to the data. While individual errors were as high as 19.8%, the overall RMS error using this approach was 10.6% (Table 2, Figure 13).

In contrast, a rating curve based on salt dilution measurements collected between December 2000 and January 2002 can be de-

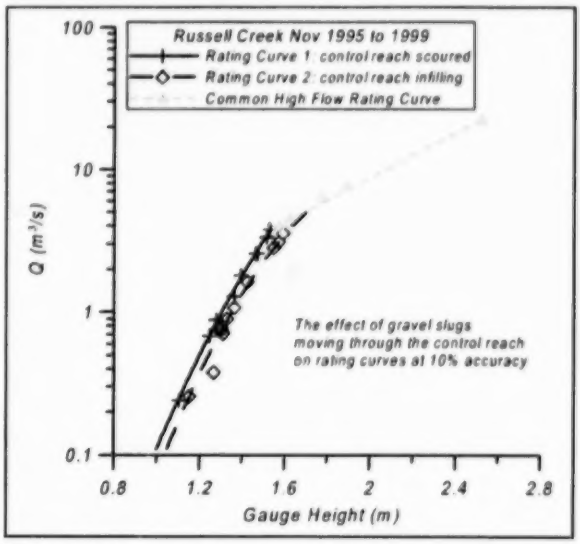


Figure 12. An alternative approach to developing rating curves applied to the Russell Creek gauging data collected after the channel erosion events. Allowing for as much as 10% error on individual measurements reduces the number of rating curves for the period to 2 low flow curves with a common high flow curve. Those curves correspond to changes in channel bed as gravel slugs are transported into and through the control reach.

Table 2. Flow rating at Russell Bridge using current metering and salt dilution; different approaches to defining rating curves.

Date	GH (m)	WSC Curve	Q1 m^3/s	Q2 m^3/s	Q salt m^3/s	Q est m^3/s	error (%)	Q est (CR) m^3/s	error (%)
29-Nov-95	2.503	common	21.800			22.648	-2.9	22.017	-0.1
08-Jan-96	1.888	8	7.580			7.206	5.2	8.308	-8.8
10-Apr-96	1.518	8	3.340			3.478	-4.0	2.942	13.5
03-Jun-96	1.475	8	2.560			2.755	-7.1	2.496	2.6
12-Aug-96	1.152	8		0.256		**0.255**	0.4	**0.217**	18.2
15-Oct-96	1.530	8	3.770			3.705	1.8	3.073	22.7
07-Jan-97	1.575	9	3.920			4.094	-4.3	3.593	9.1
11-Mar-97	1.365	9		1.077		**1.086**	-0.9	**1.228**	-12.3
06-May-97	1.614	10	4.149			4.393	-5.6	4.077	1.8
07-Jul-97	1.365	10	1.281			1.453	-11.8	1.537	-16.7
22-Oct-97	1.312	10		0.707		**0.784**	-9.9	**0.881**	-19.8
25-Nov-97	1.466	10	2.565			2.621	-2.1	2.408	6.5
22-Jan-98	1.397	11	1.798			1.762	2.1	1.789	0.5
05-Mar-98	1.249	11	0.681			0.691	-1.5	0.803	-15.2
11-Mar-98	1.304	11		0.768		**0.745**	3.0	**0.835**	-8.0
20-May-98	1.425	11		1.629		**1.527**	6.7	**1.701**	-4.2
22-Jul-98	1.280	11	0.875			0.849	3.1	0.972	-10.0
31-Aug-98	1.106	11	0.240			0.251	-4.5	0.260	-7.6
03-Nov-98	1.304	11		0.750		**0.745**	0.7	**0.835**	-10.1
05-Dec-98	1.288	11		0.759		**0.672**	13.0	**0.746**	1.8
12-Jan-99	1.626	12	4.543			4.489	1.2	4.232	7.3
12-Mar-99	1.330	12		0.895		**0.878**	1.9	**0.991**	-9.7
23-Apr-99	1.572	12		3.086		**3.103**	-0.6	**3.221**	-4.2
06-May-99	1.773	12		6.261		5.854	6.9	**6.079**	3.0
07-May-99	1.549	12		2.817		**2.810**	0.2	**2.950**	-4.5
23-Jun-99	1.593	12		3.560		**3.384**	5.2	**3.480**	2.3
RMS Error (%)							**5.5**		**10.6**
11-Dec-00	1.267	NA			0.403			0.408	-1.2
09-Nov-01	2.032	NA			9.173			9.091	0.9
20-Nov-01	1.782	NA			4.705			4.664	0.9
21-Nov-01	1.953	NA			7.445			7.513	-0.9
08-Dec-01	1.822	NA			5.018			5.260	-4.6
08-Dec-01	1.761	NA			4.486			4.369	2.7
09-Jan-02	1.567	NA			2.288			2.184	4.7
29-Nov-95	2.503	Common			21.800			21.418	1.8
RMS Error (%)									**2.7**

Notes:

Measured flows: Q1, Q2 = flow data conforming to curves #1 and #2 respectively (from WSC data), Q salt = flows measured by salt dilution and conforming to curve #3.

Calculated flows: Q est = flow calculated by rating curves as shown in Figure 12, Q est (CR) = flow calculated by curves defined by Chapman Richards equation as in Figure 13 (for curves derived from WSC data, regular text = curve #1, bold italic = curve #2).

fined by a single Chapman-Richards exponential function. All errors are within 5%, and the overall RMS error is 2.4%. Thus the salt dilution method meets the WSC accuracy criterion, while presenting a much simpler data analysis situation, and suggests relatively stable channel conditions.

6.0 GEOMORPHIC INTERPRETATION

The November 1995 events at Russell Creek that resulted in the lowering of the channel bed at the Russell Creek gauging control reach also caused two large debris flows within Russell Creek watershed. One of those debris flows occurred in an unstable gully in Stephanie Creek, and buried stream gauging equipment lower down in Stephanie Creek under a metre of gravel.

The stream rating measurements, including the measurements collected by current metering and those collected by salt dilution, reflect infilling of the channel over time. After the event that scoured about 0.5 metres of gravel from the channel bed at Russell Creek control station, gravel began to move back into the reach in slugs. Curve #1 represents the channel in its scoured condition, while curve #2 represents the channel with gravel beginning to move back into the reach (Figures 12 & 13). At the beginning of the period following the scour event, gravel moved through the reach in slugs. The rate at which the rating curve shifts occurred suggests that it took about four months for a gravel slug to move through the reach initially. Eventually over time more and more gravel migrated down the channel from debris flow deposits in upper parts of the watershed, until by the fall of 1998, the channel remained in the state defined by curve #2.

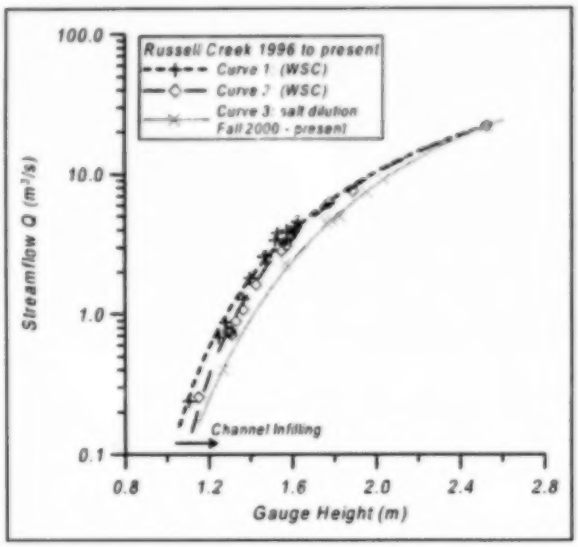


Figure 13. Three rating curves for Russell Creek show the changes in the channel bed following the erosion events of November 1995. The curves are defined by the Chapman-Richards exponential function. Curves 1 and 2 are based on WSC current meter measurements, allowing as much as 15% error on individual measurements. These are essentially the same curves that appear in Figure 12, except that each curve is defined by a single exponential function, as opposed to the two 2-part curves shown in Figure 12. Curve 3 is based on salt dilution measurements, with a maximum error of 5% and an RMS error of 2.7%. Curve 1 represents the channel in its scoured state, and curves 2 and 3 represent re-introduction of gravel into the control reach over time.

The rating curve defined by salt dilution (curve #3, Figure 13) represents further infilling of the measurement reach. It also represents a further step towards stability, as debris flow gravel deposited in lower reaches of Stephanie Creek and other points in Russell Creek become redistributed down the main Russell Creek channel.

7.0 CONCLUSION

The salt dilution method compares favorably in accuracy with current metering as a method of measuring streamflow in channels draining small (<45 km²) coastal watersheds, and appears to be capable of superior measurement precision where in-stream turbulence might interfere with current metering. Furthermore, the method is easier to apply and possibly more economical in terms of equipment cost. The salt dilution method should not be viewed as a replacement for current metering. The two methods are complementary; that is, while current metering requires laminar flow and breaks down under turbulent conditions, the reverse is true of salt dilution gauging.

With regards to the question of measurement error, it is worthwhile to revisit the assumptions of 5% accuracy in current meter measurement. We used a least-squares statistical curve fitting technique to produce the rating curves. This method defines the error in the measurements by comparison to a standard curve. In contrast, the WSC method pre-supposes the error, and then uses a graphical curve fitting technique to "force" a rating curve to fit the data to within the expected error. If a greater error is allowed (a reasonable expectation in view of the potential interferences inherent in rating turbulent channels by current meter) then the number of rating curves is reduced. This is true regardless of whether the rating curves are fitted statistically or graphically. The reduced number of curves allows for a physically based geomorphic interpretation of the changes between curves.

This study serves to validate the salt dilution method for small streams (as defined above). Two further advantages of the salt dilution method are as follows:

1. It addresses issues of worker safety, as it keeps the technician out of the water;

2. It has potential for full automation.

One of the main difficulties inherent in rating coastal streams is the unpredictable nature of storms, making it very difficult to define the upper end of the rating curve. Streams draining steep watersheds dominated by rain and rain-on-snow processes normally peak and recede rapidly, making it impossible to schedule site visits to measure high flows. The salt dilution method has the potential to be triggered automatically to measure high flows. Therefore, the next step in the development of the method should be to move towards full automation.

ACKNOWLEDGEMENTS

Technical review comments have been supplied by Scott Ferguson and Russ Gregory (WSC Nanaimo), Paul Marquis (Vancouver Forest Region, Nanaimo) and by Lynne Tolland. Thanks are extended to Lynne for inspiring us to undertake this method, following the recommendations of Geoff Kite (NHRI, Saskatoon). Thanks also to Russ Gregory, Dave Paul and Scott Ferguson for the many interesting and useful discussions about technical methods, and for supplying the flow rating data. Technical editing of this report was by Fred Dawkins.

Disclaimer: This report is not intended as a criticism of Water Survey of Canada, its methods or its technicians, but as an objective documentation of an alternative method that might assist WSC to overcome operational difficulties inherent in gauging turbulent channels.

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